Engineers Australia
Engineering Heritage Victoria

ENGINEERS
AUSTRALIA
Victoria Division

Nomination

Engineering Heritage Australia Recognition Program

Flight Memory Recorder – Dr David Warren's Invention

June 2015

Front Cover Photograph Caption

Figure 1: The original (1958) ARL Flight Memory Recorder, capable of storing the Cockpit speech and eight instrument readings per second for the four hours prior to an accident

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1 Introduction

In 1953 Dr David Warren led a team (Walter Boswell, Walter Francis Lane Sear and Kenneth Fraser) of engineers, scientists and enthusiasts alike in developing what has been historically referred as the origins of the modern black box flight recorder which is utilized in all commercial aircraft today. The technology involved was based upon a cockpit voice recorder (CVR) and a form of flight data recorder (FDR).The technologies involved previously existed in some form or another. It was Dr David Warren's innovation and vision however that led to the amalgamation of the two separate recorders into a single system, which was referred to as a Flight Memory Recorder, that could withstand temperatures over 1,000° Celsius and several hundred g-forces, allowing aircraft wreck investigators to analyse the data from several vital aspects of a plane, as well as listen to what was occurring in the cockpit prior to an aviation disaster or incident.

The main driving force behind the creation of the black box flight data recorder was a series of inexplicable aviation disasters involving the first commercially jet-powered airliner, the famous de Havilland Comet[1]. "Aircraft Engineers and Scientists all around the world were so perplexed"[2]. During a series of meetings and consortiums trying to address the incomprehensible disasters David Warren purposed that whilst it was difficult to trace the cause of a crash after the event, there would be a good chance that the flight crew's conversation prior to an accident very may well reveal critical information whilst trying to deal with the emergency. The concept however raised little interest within the community and was overlooked for quite some time. Even with a working prototype being trailed pilots, the aviation authorities and all those involved were far from enthusiastic about the idea. It wasn't until 1958 when the Secretary of the UK Air Registration Board saw the device on a chance visit to the ARL that an interest was finally sparked. Whilst the device was further developed overseas it was the catalyst which lead to Australia being the first nation to have mandatory Flight Data Recorders and Cockpit Voice Recorders installed in all commercial aircraft. The rest of the world soon followed.

David Warren's concept and vision provided a means for retrospective analysis which was previously unavailable and provided invaluable means for diagnosing catastrophic failures in aircraft as well as shed light on what was really occurring on the aircraft during the vital moments. The device created has immense historical significance as it paved the way for modern aviation safety standards.

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[1](David Waren, 1998)
[2](David Waren, 1998)

2. Heritage Nomination Letter

The Administrator
Engineering Heritage Australia
Engineers Australia
Engineering House
11 National Circuit
BARTON ACT 2600

Name of work: Flight Memory Recorder - Dr David Warren' Invention

The above-mentioned work is nominated for an award under the Engineering Heritage Recognition Program.

Location, including address and map grid reference if a fixed work: Prototype material currently in the collection of Melbourne Museum

Owner (name & address): Museum Victoria, GPO Box 666, Melbourne Victoria 3001

The owner has been advised of this nomination and a letter of agreement is attached at Appendix 8.

Access to site: The prototype material is currently not on public display.

Nominating Body: **Engineering Heritage Victoria**
Owen Peake
Chair
Engineering Heritage Vic

June 2015

3. Heritage Assessment

3.1Item Name: Flight Memory Recorder

3.2Other Former Names: Black box, Flight Voice and Data Recorder

3.3 Location: Incorporated in all commercial airliners/ Melbourne Museum

3.4 Address: Melbourne Museum, GPO Box 666, Melbourne Victoria 3001

3.5 Suburb: Melbourne

3.6 State: Victoria

3.7Local Government: City of Melbourne

3.8Owner: Museum Victoria

3.9Former Use: Museum display piece, prototype flight data recorder and voice recorder

3.10 Designer: David Warren, Kenneth Fraser, Lane Sear, Walter Boswell

3.11 Maker / Builder: ARL Melbourne

3.12Year Commenced: 1953

3.13Year Completed: 1962

3.14Physical Description: The flight and data recorder is a box made of aluminium insulated using asbestos, it incorporates a single wire recorder which puts multiple channels onto the wire. There is also an encoding device for mounting in the aircraft and a decoding device which is constructed of timber and metal. This device is used to decipher the channels recorded onto the wire recorder.

3.15Physical Condition: The physical condition of the flight recorder prototype is burnt black because it has undergone fire tests. The asbestos insulation is also crumbling.

3.16 Modifications and Dates: The Flight Memory Recorder, which was only ever developed to a pre-production prototype stage, was complete by late 1961, with the project commencing during 1953. The device underwent its maiden 'test flight' on the 23rd of March 1962, departing from Essendon Airport in Melbourne. As Dr David Warrens invention was refined and redeveloped abroad by unaffiliated companies in the years to precede there have been no such modifications or alterations made to the original unit which underwent the historical 'test flight' from Essendon[3].

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[3] It is worth noting that the spools of magnetic recording wire utilized as the storage medium have since tangled and knotted quite severely, due to general wear and tear. It is in such a state that it's unrepairable and would require replacing of the spools. In order to preserve the devices historical significance and originality it obviously has not been repaired and remains as is

The dimensions of the unit when built, and of present measures approximately 200 mm in length by 100 mm in width by 180 mm in height.

3.17 Historical Notes: As a direct result of Dr David Warren and his teams Flight Memory Recorder, the first device capable of recording multiple flight instrument data signals as well as cockpit voice conversations, Australia became the first nation in the world to make the technology mandatory in commercial aircraft in 1967[4]. In light of Australia's establishment of a world first standard other nations, in particular the United States and the United Kingdom, would adapt similar protocols in the immediate years to follow.

The site at which most of the work took place was at the Aeronautical Research Laboratories (a DSTO -Department of Science and Technology Organisation facility) research and testing facilities located at Fishermans Bend in Melbourne. The DTSO is a branch of the Commonwealth Department of Defence.

Whilst substantially renovated the building still maintains the same location and can be found on the banks of the Yarra River at 506 Lorimer Street, Fishermans Bend VIC 3207.

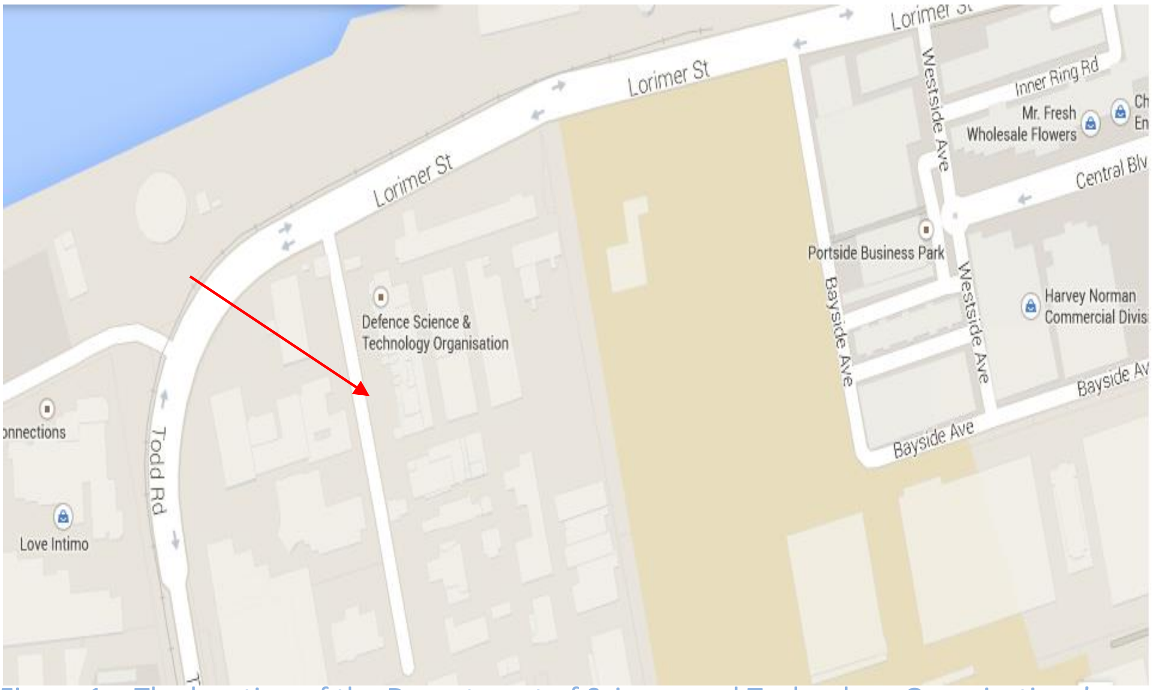

Figure 1 – The location of the Department of Science and Technology Organisations' Melbourne facility.

[4](David Waren& Ken Fraser, 1998)

4. Assessment of Significance

4.1 Historical Significance

David Warren's flight data and voice recorder was one of the first flight data and voice recorder designs. It was the first to contain a cockpit voice recording device. The device is historically significant because all modern 'black boxes' contain a cockpit voice recorder, the flight data and voice recorders have been the major cause of the aviation industry being so safe and it also is the only good way for engineers to know what happened onboard an aircraft prior to crashing and they can find the reason for the fault

4.2 Historic Individuals or Association

The team involved with this voice-plus-data recorder project were David Warren, Walter Boswell, Walter Francis, Lane Sear, and Kenneth Fraser

David Warren was a chemist and aviation fuels specialist who came up with this original idea while he was involved in research as to why the Comet disasters kept occurring. Around this time David Warren noticed an interesting new device at a trades fair: the first portable voice recording device which was made up of a spool of very thin steel wire that runs across a head and can record voice. This recording device was the inspiration for David Warren to start development of the voice-plus-data recorder which used this concept of a wire recorder with some modifications. David Warren's recorder was able to record multiple signals onto one wire by varying the frequency at which the different data segments were recorded.

Kenneth Fraser and Lane Sear were engineers who designed the circuit diagrams for the electrical parts for both the onboard system and the base system. Kenneth Fraser's involvement with the project started in 1961 with the aim to update the early model of the flight data recording system to a preproduction standard suitable for recording cockpit voice and data in a fireproof and crash proof casing. Ken Fraser was involved (a minority part) of the design of the airborne systems (signal circuit design) as well as the high power system (recorder drive etc), he also had a majority involvement with the design of the data recovery and audio circuits used in the airborne unit.

Walter Francis Lane Sear (Lane Sear) was a qualified electrical designer who had equal share of the final design with Kenneth Fraser.

Lane Sear had a majority involvement in the design of the airborne system (signal circuit design), he also had a minor involvement in the design of the data recovery and audio circuits used in the airborne unit.

Walter Boswell was a technical assistant whose main role with the flight-plus-data recorder project was to convert the designs of Kenneth Fraser and Lane Sear into usable hardware.

Aeronautical Research laboratories (ARL) were the government organisation that David Warren and his team worked for and under whom the flight recorder was developed.

ARL was founded in 1939 on a four hectare site in Fishermans Bend, Victoria. The majority of the research done in the early years by ARL was in the military field particularly to do with aviation research. In these war years the ARL designed some aircraft: the boomerang, CA11, and CA15.

In 1941 the first wind tunnel was installed at the ARL site, and they also commenced aircraft accident investigations.

4.3 Creative or Technical Achievement of the Flight Memory Recorder

Dr David Warren and his team of co-workers demonstrated extreme ingenuity and creativity when working on the Flight Memory Recorder. The device itself is technically significant as firstly it established and tackled the challenges posed to the technically minded regarding the recording of upwards of 8 channels of flight instrument data, as well as the cockpit voice recordings, with gusto and uttermost professionalism. Secondly the Flight Memory Recorder provided a solid foundation upon which all later developed 'black box's' could build upon and further improve.

Dr Warrens solution to the problem was an ingenious method (and in the 1960's considered truly state of the art technology) which utilized a form of time and frequency based multiplexing to allow the various parameters not only to be recorded, but collectively recorded on the same single channelled medium, magnetic steel wire[5]. Whilst later developed black box recording devices moved toward utilizing multi-channel magnetic tape and as of late solid state memory chips, the principles and methods which the team developed would still prove relevant.

In conjunction with the Flight Memory Recorder the team also developed what was referred to as the Ground Station Recovery Unit, again a technical achievement. This device had the ability to unscramble the raw data that had been magnetically recorded on the steel wire and assort the data in such a way that each instrument could be individually assessed and analysed.

In an era long before digital electronics the ability to simply record various pieces of an aeroplanes instrument data was a considerable achievement. This amalgamated with the recordings of cockpit voice conversations; all accomplished on a single channel medium was and is still considered extremely sophisticated in its own right.

[5] The wire was specifically designed for this project, measuring 0.005 mm in diameter

4.4 Research potential of the Flight Memory Recorder

Dr David Warrens Flight Memory Recorder has undergone extensive thorough research in the years preceding its construction, as it was truly a state of the art device. The original prototype itself remains in the archives of the Melbourne Museum, now property of Museums Victoria.

Whilst the device isn't currently on display, arrangements can be made to access the Flight Memory Recorder should further research be required.

There does however remain an area or two where little to no information is available. These include:

> No original schematic of the Memory Recorder. Whilst the basic principles of how the device operated can be understood, the finer details are scarce. This is a difficult area to research as the device is old, slightly fragile and cannot be taken apart as there are severe tangles in the spooled steel wire recording medium, which would have to be destroyed in order to delve deeper
>
> There is only one remaining member alive of the original team that worked on the ARL's Flight Memory Recorder, Ken Fraser. Sadly Dr David Warren and other team members are no longer with us, however their legacy lives on through their work, their families and the development of a world first innovation. Because of these reasons it's difficult to gain insight into the thought process of how various keys decisions critical to the unit were made and how conclusions were reached.

4.5 Social significance of the Flight Memory Recorder

The Flight Memory Recorder, known later as the 'Black Box' Flight Data Recorder and Cockpit Voice Recorder, had a radical effect on airline safety and helped elevate 'flying' to the safest form of public transport[6].

Even in Australia, with a long history of high safety levels amongst it airlines, safety was improved as the 'Black Box' systematically and quickly identified the causes of air crashes, and with the assistance of national air transport authorities and the aircraft manufacturers, found solutions for the problems identified.

This change was a part of the social attitude to 'flying' in Australia. People saw 'flying' as a 'safe' form of public transport and as time went by technology also made 'flying' cheaper and more accessible. Australians are now more likely to fly to their destinations as people in many other countries take a train or a bus. 'Flying' has become socially 'normal' and 'acceptable'.

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[6] Wikipedia, New Scientist Space, Flight into Danger, 7 Aug 1999. This article found that air travel was the safest way to travel on the basis of 'Deaths per billion kilometres'.

Much the same has happened around the world although Australians, because of our sparse population and large distances, remain huge users of airline services

4.6 Rarity relating to the Flight Memory Recorder

The concept of a flight data recorder, whilst not the conventional device associated by all today, did previously exist prior to Dr David Warrens design in the early 1960's. One of the earliest documented reports of a flight data recorder can be dated as early as 1939[7]. The device, better known as a 'type HB' recorder was conceptualized by François Hussenot and Paul Beaudouin whom were of French descent. The system was able to record basic data elements such as altitude and speed via an array of mirrors and lights which would alter light intensity with a corresponding increase in the measured magnitude. These deviations were recorded upon a photographic film based storage medium, which could then later be deciphered.

The first widely acknowledged modern flight recorder that is the sophisticated, robust mechanical 'black box' type device all would be familiar with wasn't developed until three years later, during 1942[8]. The 'Mata Hari' as historically referred too, was the brain child of a Finish Aviation Engineer, Veijo Hietal and was capable of storing the flight instrument data for a few vital elements. It was utilized by the Finish military and incorporated with fighter aircraft which were trialled throughout World War II.

Whilst this demonstrates that others too had previously toyed with the idea of flight data recorders for aircraft, Dr David Warrens invention is unique due to the fact that his Flight Memory Recorder was the first device in the world which was capable of recording both the flight instrument data and cockpit voice recordings simultaneously, all on a single channelled medium. A truly rare innovation that was far ahead of its time forever changed aviation safety standards as in 1969 Australia became the first nation to require the mandatory recording of flight data and cockpit voice conversations, a practice that was later adopted around the world[9].

The technology physically utilized at the core of the system, a steel wire spooled recording system was common practise for simple sound recording purposes during that time. Dr Warrens Flight Memory Recorder however differed to the common practise which required the changing of spools when the recording medium ran out, creating an automatic feedback loop which would re-record over the old data stored every 4 hours. The use of magnetic steel wire as a recording medium was eventually phased out being replaced by 8 track magnetic tape, which has now been superseded by means of solid state digital recording.

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[7]Denis Beaudouin, Chloé Beaudouin &*Charles Beaudouin: une histoire d'instruments scientifiques*, 2005, page 207.
[8]Joe Janes, *Documents that changed the world – Airplane Black Box / Flight Data Recorder,* 2014, University of Washington
[9]David Waren & Ken Fraser, *The Black Box: An Australian Contribution to Air saftey,* 1998

Dr David Warrens Flight Memory Recorder utilized a series of complex methods such as time and frequency based multiplexing to solve the scientific challenges posed by the task of storing 8 channels of flight data as well as cockpit voice recordings on a single channelled medium. This pushing of scientific boundaries was achieved by Dr Warren and his colleagues with uttermost professionalism and too the highest standard. Whilst the Flight Memory Recorder was later developed overseas, it was this invention from which all modern 'black box's' have evolved

4.7 Representativeness of the Flight Memory Recorder

Although the ARL Flight Memory Recorder, as developed by David Warren and his team, was not the first attempt to capture data from aircraft involved in air crashes, it was the first device which resembles the modern 'Black Box'.

In this regard the relics held by Museum Victoria mark a dramatic shift in thinking and a substantial step-change in the development of the technology.

The Museum Victoria collection relating to the Flight Memory Recorder, including important prototype components is therefore a key marker representing this major technological breakthrough.

A full spectrum of artefacts representing the development of the 'Black Box' would need to include:

Examples of early devices developed prior to the ARL/Warren work.

Prototypes of the ARL/Warren work.

Examples of more recent 'Black Boxes' which now incorporate larger amounts of data capture and greater robustness as a result of using 'solid state' digital electronics which can tolerate much larger 'g' forces.

Hence the Flight Memory Recorder is a key element in the representativeness of artefacts which tell the full story of the 'Black Box'.

5 Statement of Significance

What is Significant?

Dr David Warren's Flight Memory Recorder was a key development in the search for a robust, automatic device to record flight deck conversations for a short time prior to an incident or crash.

The device was developed within the Aeronautical Research Laboratory (ARL) with the first prototype built in 1962 in Melbourne.

The device consisted of a small steel wire reel-to-reel audio recorder enclosed in a shock and fire resistant enclosure. The system also included ancillary devices to code data in the aircraft to prepare it for the recorder and a device to retrieve the recorded data on the ground following recovery of the recorder.

It should be noted that in subsequent developments the device evolved into two components, housed separately but usually close together in the tail of the aircraft:

Cockpit Voice Recorder (CVR)

Flight Data Recorder (FDR)

The devices now also incorporate beacons to enhance the search for the 'Black Boxes' following a crash.

How is it Significant?

The Flight Memory Recorder is scientifically and technologically significant as it represents a major world breakthrough in the search for a device to record information immediately prior to an air incident or crash. All modern 'Black Boxes' can be traced back to the ARL/Warren work.

The Flight Memory Recorder is historically significant as it marks the beginning of systems and methodologies to significantly improve air safety. In this regard the invention is part of the global uptake of air transport towards the very high levels of usage and safety we enjoy today.

The Flight Memory Recorder is culturally significant as it was a key element in the improvement in aviation safety which helped 'sell' air travel as a safe and efficient method of travel. Air travel is now regarded as the safest form of travel in a global market for travel which is still growing at a rapid rate.

The flight recorder not only saves thousands of lives when its purpose is fully utilized, it also changed the airline industry and the way it operates. Air safety has become a major marketing tool for the industry. Also, the evolution of new design methods and materials by aircraft manufacturers has increased the actual safety of modern airframes.

The inventor Dr David Warren was a young scientist who was working in an air crash investigation, specialised in fuel combustion at the department of Aeronautical Research Laboratory in Melbourne. During the early 1953 he was involved in the analyses of the probable cause of the crashes of Britain's first civil jet airliner the De Havilland Comet after series of mysterious fatal accidents.

The Flight Memory Recorder idea occurred to Dr Warren during this work. He believed that such a device would be valuable to crash investigators to determine the cause of the crash. The idea came after his visit to an exhibition in Melbourne and saw German's pocket size 'Minifon' wire tape recorder.

The idea was not well received in ARL at first, neither was it among other's aviation authorities in Australia. When the 'Black Box' began to "take off' internationally Australia still remained slow behind the idea" [10].

Dr David Warren endured much political and social adversity over 14 years after he first conceived the idea before his original 'Black Box' became mandatory in commercial aircraft. According to David Warren "Australia fumbled and lost every opportunity to get in at the beginning of a world-wide business" because of "fear of a novel innovative idea, fear of taking risks, meant the invention was lost to other countries".

[10] G J 1999.

6 Area of Significance

State, National and International

State significance is inferred by the inventions being made at ARL which was based in Victoria.

National significance was inferred by Australia being the first nation in the world to adopt compulsory use of flight data recorders in airliners.

International significance is inferred due to the technology, first mandated in Australia, spreading around the world and becoming ubiquitous in airliners worldwide, in many military air forces and in more recent times in light aircraft.

Well publicised events such as the losses of MH370, MH17 and Air Asia QZ8501 have underlined the importance of flight data recorders internationally.

7 Heritage Listings

Dr Warren’s Flight Memory Recorder is not listed by the National Trust, Heritage Victoria or the National Heritage List.

8 Interpretation Plan

8.1 General Approach

The interpretation Plan will be carried out in accordance with the 2012 edition of the Guide to the Heritage Recognition Program which can be found on the EHA web site at www.engineeringheritage.com.au

This will consist of interpretation developed in liaison with the owner (Museum Victoria) and the Heritage Recognition Committee. The interpretation will be unveiled at a public ceremony probably in November 2015.

Museum Victoria, whose collection includes components of the Flight Memory Recorder have agreed in principle in writing to:

Place components of the Flight Memory Recorder on display at the Melbourne Museum. Note that the components are currently in store at the Melbourne Museum.

Discuss suitable interpretation with Engineering Heritage Victoria.

Conduct an unveiling ceremony for the new display including the Heritage Recognition.

It is anticipated that the appropriate interpretation in this instance will, most likely, be a "mini-panel" as used elsewhere where appropriate interpretation by the owner is already in place. This could be in the vicinity of 400 mm wide x say 800 mm high formed of digital printing on vinyl film on an aluminium substrate. The panel would incorporate a representation of the award disc presented which is likely to be an Engineering Heritage International Marker, subject to the decision of the national Heritage Recognition Committee.

8.2 General Attributes of the Interpretation Panel

1) A title **"Black Box Flight Recorder"**
2) A sub title: **"An Australian Invention"**
3) Logos of Engineers Australia, Museum Victoria and Victorian Government to be incorporated.
4) A small size representation of the EHA marker plate
5) The date and other details of the marking ceremony.
6) Text should be 24 point Arial Bold
7) Maximum text should be 250 words
8) Historic Photographs of the Flight Memory Recorder

8.3 The Interpretation Panel
1) Size to be nominally 800 mm high by 400 mm wide, i.e. a 'mini panel'
2) The panel is to be constructed of per diagrams in **Appendix 7**.

8.4 Possible Interpretation themes for Interpretation Panel

This will be a standard panel with the following three themes:

- History of Flight Recorder
- David Warrens Prototype

8.5 Preliminary Text Block for Interpretation Panel

8.5.1 History of Flight Recorder

There have been many different flight recorders created over the years, early versions such as the HB recorder invented by Francoise Hussenot used photography of the instruments and cockpit. Then recorders moved on to recording instrument readings by etching onto foil or magnetic tape. Dr David Warren was the first person to invent a flight recorder that recorded by voice and instruments onto a single wire recorder, this flight recorder was able to record 8 instruments and 1 voice channel for 4 hours.
Flight recorders became mandatory on Australian commercial airlines in 1967, following a crash of a Fokker Friendship in good weather.
All modern flight recorders must be able to withstand 1000°C and over 3600 g's. Most modern flight recorders also record 17-25 hours in a continuous loop.

129 Words

8.5.2 David Warrens' Prototype

David Warren's prototype consisted of a single wire recorder encased in a fire and shock proof casing. This flight recorder was the first recorder to record both voice and instrument readings. This prototype started development in 1953 and its first test flight was in 1962, the prototype was developed by Dr David Warren, Kenneth Fraser, Lane Sear, and Walter Boswell, it was developed at the Aeronautical Research Laboratories in Melbourne. Once the prototype was completed there was no interest from companies in Australia to manufacture it but there was however interest in the UK. It was then produced by S Duvall & Sons in the UK, in an iconic 'Red Egg' design.

112 Words

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Appendix 1 Images with Captions

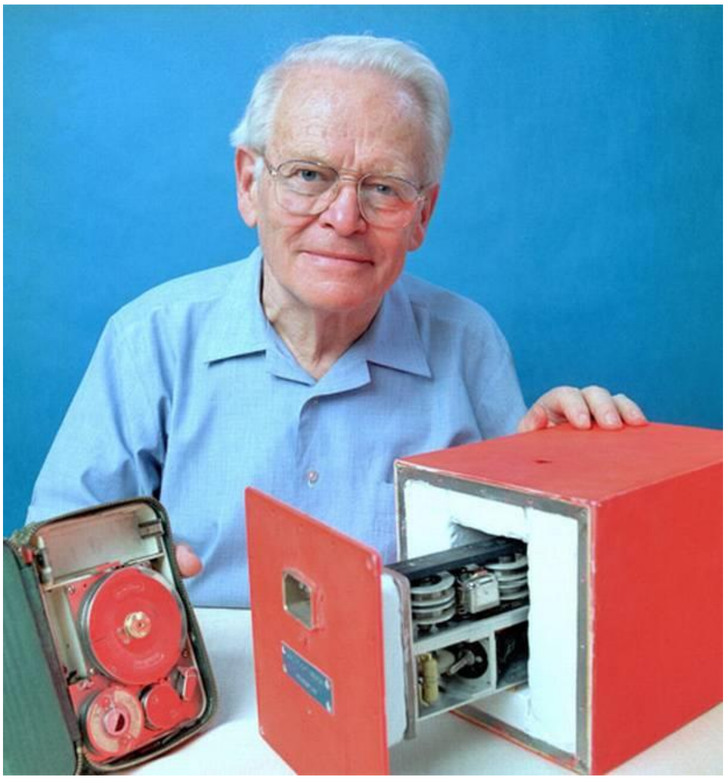

Figure 1 -Dr David Warren and his prototype flight recorder (David Warren, 1996)

Figure 2 -ARL flight memory aircraft unit (Owen Peake, 2014)

Figure 3 -Original prototype recorder which has been through fire testing (Owen Peake, 2014)

Figure 4 –ARL's Flight memory Ground equipment (Owen Peake, 2014)

Figure 5 -ARL flight memory onboard unit (Owen Peake, 2014)

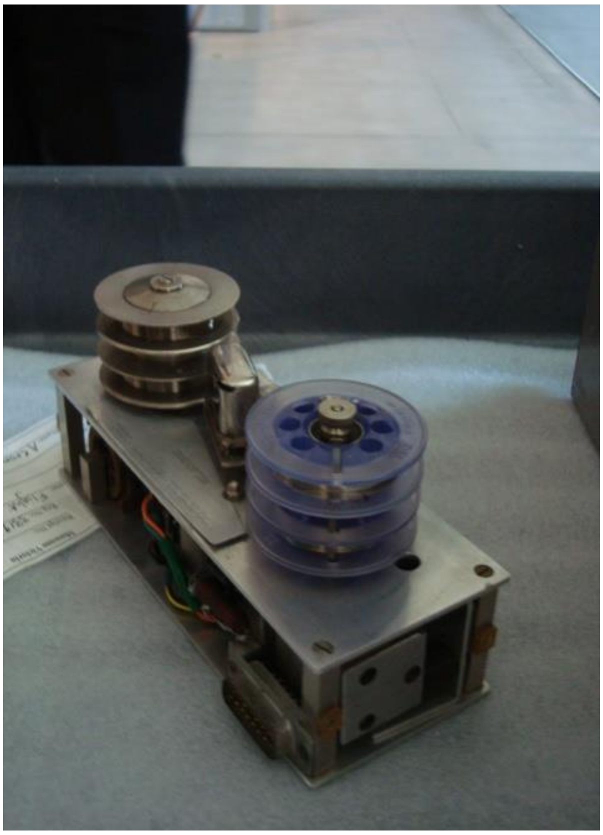

Figure 6 – A Single wire recorder used in the ARL flight memory recorder (Owen Peake, 2014)

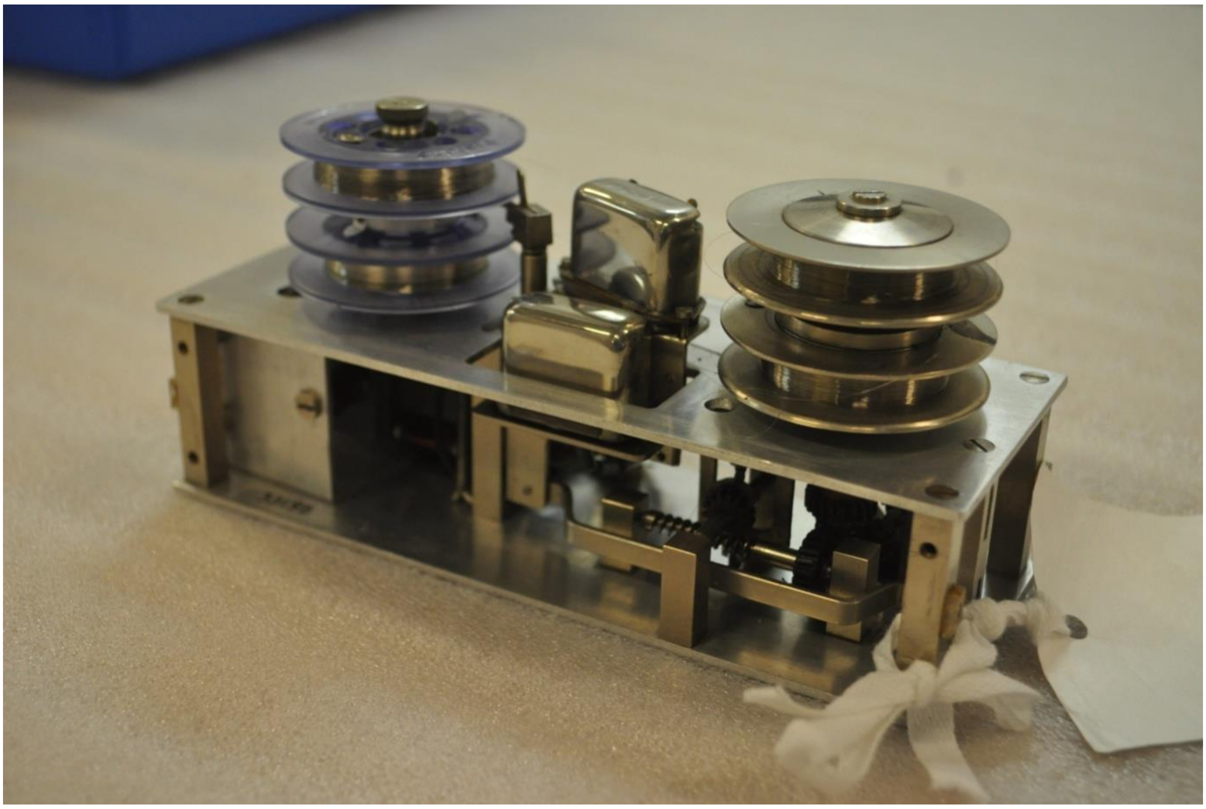

Figure 7 -Single wire recorder used in the ARL flight memory recorder (Owen Peake, 2014)

Figure 8 -All the components of the ARL Flight Memory unit (Owen Peake, 2014)

Figure 9 -Prototype jettison able recorder designed to be fixed to the outside of the aircraft (Owen Peake, 2014)

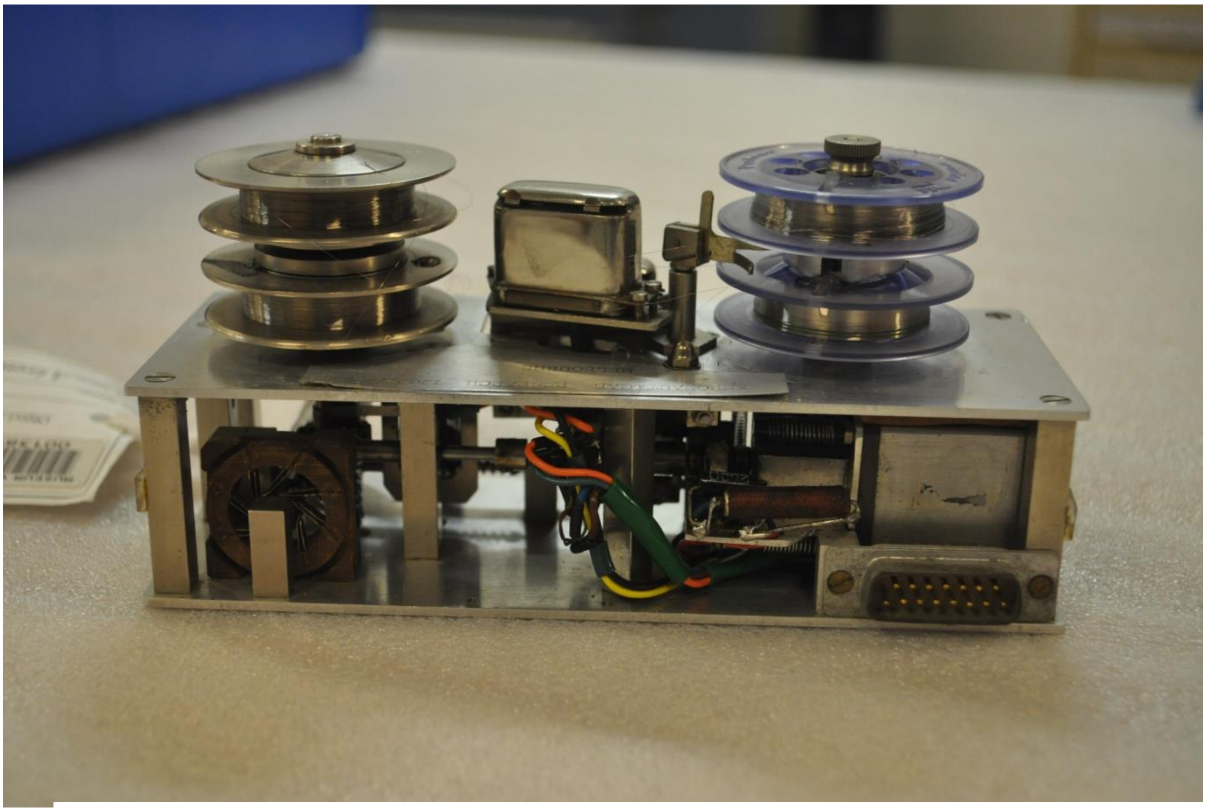

Figure 10 -Single Wire Recorder showing internal mechanisms (Owen Peake, 2014)

Figure 11 – An example of modern flight recorders (ATSB, 2014

Appendix 2 Black Box Evolution

Figure 1 Flight Memory Recorder Prototype (Peake, 2014)

Flight recorders of varying levels of sophistication have been in existence almost since the beginning of manned flight.
The Wright brothers are said to have installed a device on their first flyer of 1903 that logged such parameters as propeller rotation and airspeed, and Charles Lindbergh, in his epoch-making flight across the Atlantic in 1927, employed a barometric device that sensed changes in air pressure (and therefore altitude) and recorded these changes by tracing lines on a rotating spool.[11]

In 1939 Frenchmen François Hussenot and Paul Beaudouin invented the type HB flight recorder, this flight recorder was a photographic based recorder which recorded onto an 8 metre long 88 mm wide photographic film, these recorders remained in use in French centres into the mid-seventies.

Figure 2 "Red Egg" David Warrens Flight Memory Recorder produced by S Davall and Sons(Powerhouse Museum, 2010)

Another early design of a flight data recorder was the invention of Vic Husband and Len Harrison, their recorder recorded the flight data onto a copper foil using a method of indentation, the foil was advanced at intervals and new readings taken allowing investigators to see the way the controls were set at each interval.

Dr David Warren (Australian Research Laboratories) is credited with the invention of the flight voice and data recorder, this was the first time that both cockpit voice and aircraft flight data was recorded using one device. Australia was the first country to make flight recorders mandatory on all commercial airliners in 1967[12]

After David Warren's device the black box flight recorder continued to develop, from the steel wire recorder used by David Warren to the use of magnetic tape. Modern flight recorders use solid state technologies to record data.[13]

David Warren's flight data and voice recorder could only record four hours of data before beginning to rewrite over the old information[14], his device could also only record voice and

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[11](Britannica, 2013)
[12](DSTO, 2014)
[13](Britannica, 2013)
[14](Flight Memory an australian contribution to air safety, n.d.)

8 different instruments. Modern flight recorders now record a minimum 2 hours of voice, and 25 hours of data into solid state memory, another requirement of the flight recorder is that it can withstand 3,400 g's, temperatures as high as 1100°C, and withstand pressures of 6000 metres below sea level. Modern Flight recorders are also fitted with a sonic beacon for when the recorder is below the surface of water.

Figure 3 Modern Flight Recorder (ATSB, 2014)

Appendix 3 The Technical Workings of Dr David Warren's Flight Memory Recorder

The Flight Memory Recorder Dr David Warren proposed was centralised around a device capable of recording and storing both the Cockpit Voice Recorder and the Flight Data Recorder. Dr David Warren proposed that data should be logged utilizing a steel wire recording medium. There was much debate as to the recording medium to be used. The two options available at the time were either an eight track recording tape, which was capable of holding more data (in a conventional sense, as it had 8 separate tracks) however was far less resilient in terms of durability. There were fears that they wouldn't be able to survive the harsh conditions a black box might be subject too. It was because of this reason the steel wire recording was selected, it could withstand the brutal conditions.

This obviously posed several technical challenges. The Flight Memory Recorder had to be able to record eight separate channels of flight instrument data as well as uninterrupted voice recordings from the cockpit, all on a single track. It was concluded that four hours of pilot voice recordings prior to an aviation incident were sufficient, with the data simply re-recording over itself on regular intervals. The wire selected was made of special steel with a diameter of 0.005 mm[15].

It was decided that the most effective and practical way to achieve the desired outcomes would be to restrict each of the individual channels to their own specific frequency band. This created some form of isolation between the numerous signals which enabled each to be individually deciphered and interpreted if and when the data was to be accessed. This igneous method is what's known as time division multiplexing. Basically time division multiplexing is a process whereby one channel is utilized in such a way that it can be broken down into several sub-channels. The given time domain (in this instance, one second blocks) is fragmented down into several separate sections, which essentially allows each signal to take turns or bursts at sending data through the channel.

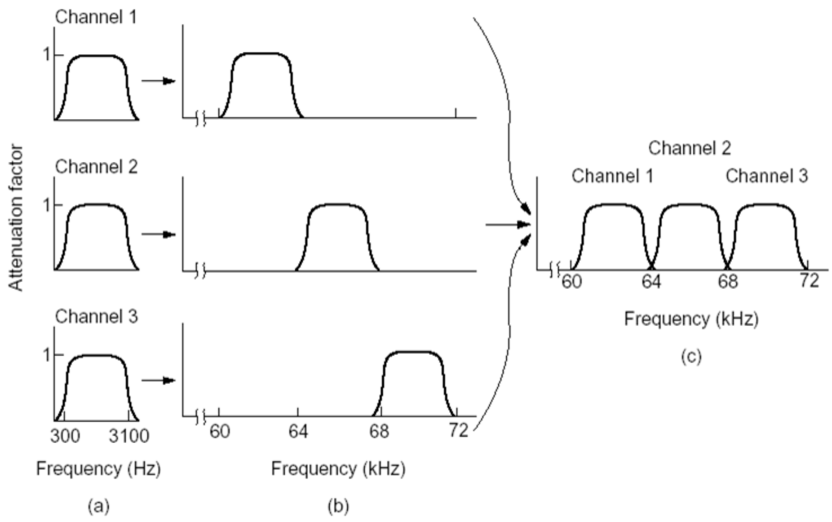

Figure 1 – Basic Principles Time Division Multiplexing (Cooke, 1989)

[15](David Waren, 1998)

In the instance of the Flight Memory Recorder the signals received from the various transducers were multiplexed at a rate of 24 readings per second, or in other terms around 40 ms each per second interval.

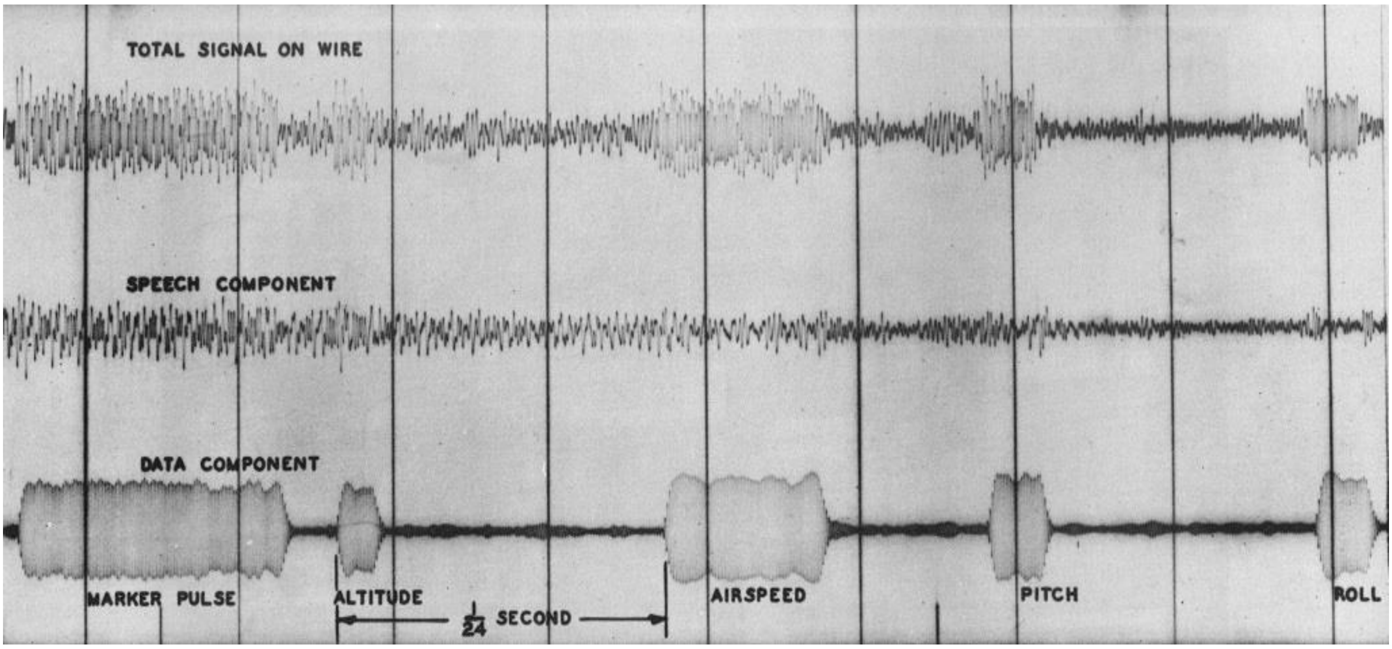

Figure 2 – A segment of the cockpit speech and instrument data recordings from the Flight Memory Recorders 1962 test flight (David Waren, 1998)

The above diagram (Figure 2), which is actual data recorded by Dr Warren's device during a test flight, demonstrates that there is a clear isolation between the various channels allowing each to be individually analysed.

The speech component of the total signal however is entirely unlike the eight pieces of instrument data being recorded. This is due to the fact that the signals from the various instruments could still be accurately interpreted and assessed while being sampled at what is considered a relatively low rate[16] (i.e. the individual instrument recordings weren't 'entirely continuous' as per say as they were only allocated 1/24th of a second due to the multiplexing). Speech recordings on the other hand obviously cannot be accurately interpreted if they were multiplexed into segments, as you'd miss the bulk of the voice recordings while the instrument data is being logged.

To address this issue the Cockpit Voice Recorder, or speech component was an uninterrupted signal recorded separately to the instrument data.

[16]Flight data parameters recorded included information such as the aeroplanes altitude, current airspeed, pitch and roll constraints as well as the cabin pressure.

The two individual signals (Flight Data Recorder and Cockpit Voice Recorder) were then modulated over a carrier signal.[17] As the speech component was recorded at a different frequency to the flight instrument readings, when modulated or combined with the carrier signal it would allow both too be clearly recorded on the same channel without any distortion or crossover between the two.

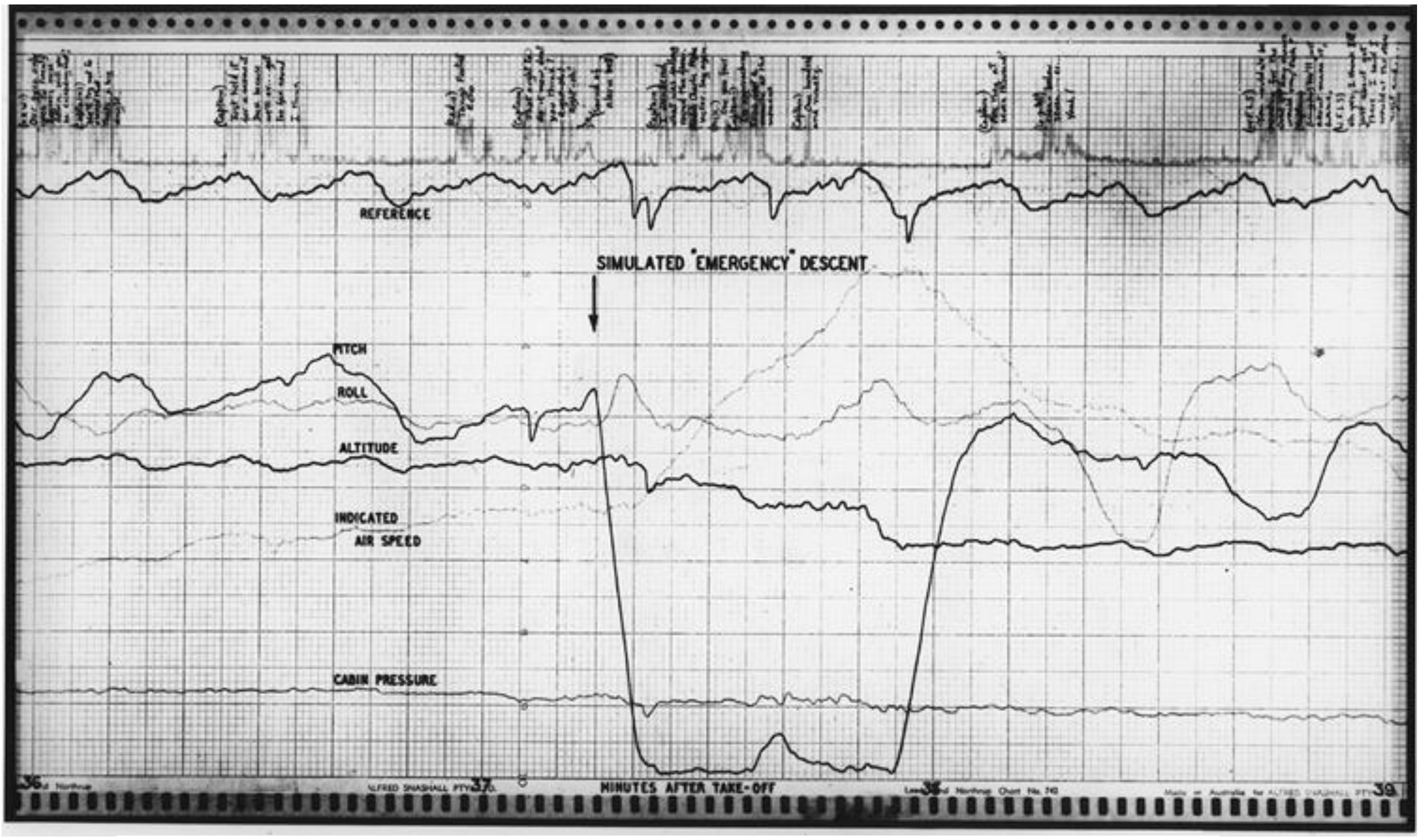

Figure 3 – A chart print out from the Flight Memory Recorder taken from a test flight (David Waren, 1998)

[17] (David Warren, 1998)

In conjunction with the Flight Memory Recorder itself the Aeronautical Research Laboratory had to build and design special ground equipment which was capable of deciphering the multiple instrument readings on the single channel into their respective individual signals, known as the Ground Station Recovery Unit.

Figure 4 – The ARL's Ground Station Recovery Unit (David Waren, 1998)

Recovering and deciphering the data from the wire recording spools again posed several technical challenges in their own right.

In the event of an aviation incident the most vital step was to obviously recover the Flight Memory Recorder, or at very least the wire recording spools from the Flight Memory Recorder
Once located the first task to be undertaken was to separate the Cockpit Voice Recording from the Flight Data recordings[18]. When isolated from the carrier signal the voice recordings could be rather simply replayed and analysed. The Ground Station Recovery Unit users had the ability to alter the gain (or amplification) of the voice signal, the pitch and tone as well as the volume. By altering these

[18](David Waren, 1998)

three parameters it was possible to manipulate a recording with a degree of interference into a relatively clear and audible audio signal.

The Flight Data recordings however had to undergo a process of de-multiplexing, which is basically the reverse of multiplexing. The raw Flight Data signals were again split up into 1/24th per second segments and then re-combined with the corresponding segments taken at each interval. This essentially rebuilt the respective individual instrument readings and allowed them to be replicated.

For conveniences sake the Ground Station Recovery Unit had the ability to display the interpreted data in several different formats. These included the printing out of data in its raw form, which is now looked back upon as a pseudo-digital, dot matrix type display.

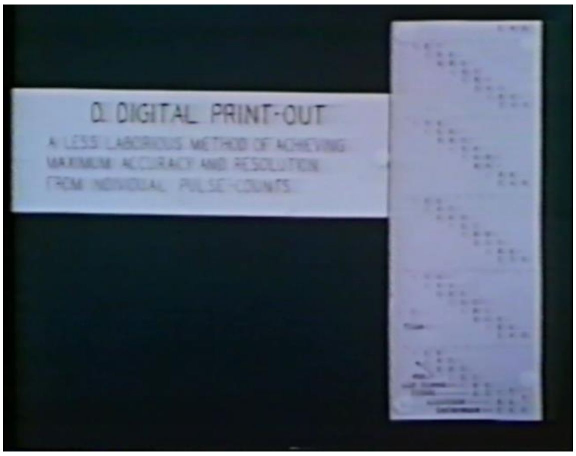

Figure 5 – The Pseudo Digital Dot Matrix Print Out of Flight Instrument Data (David Waren, 1998)

(IS THIS CLEAR ENOUGH, IF NOT DELETE AS Couldn't FIND ANOTHER SUITABLE IMAGE)

The data could also be displayed purely as a continuous graphical record, or thirdly could be displayed as a visual graphical record in constant comparison with the Cockpit Voice Recordings, as to allow for specific interpretations to be made relevant to what was occurring within the cockpit.

It was from this data in its various forms that those analysing the Flight Memory Recorder were able to interpret these raw statistics and render them into useful, easily comprehendible and reliable information.

Further information regarding the technical workings of the Flight Memory Recorder and Ground Recovery Unit can be found in Appendix 7.

Appendix 4 Historical Significance Timeline

1934, October 19, David Warren's father was killed in one of Australia's first aviation disasters, Holyman Airways De Havilland DH 86 which was lost in the Bass Strait[19].

1937, Australia, Federal Government made a decision to establish a laboratory to meet the requirement of the RAAF, civil aviation, private aviation and automotive industries by way of research into aerodynamics, structure and materials, engine and fuel and instruments[20].

1939, Australia, Dr L.P. Coombes D F C BSc, FRAES, FAES appointed as Chief of the new Division of Aeronautics of the Council for Scientific and Industrial Research (CSIR), took over area in Fishermans Bend as a site now known as Aeronautical Research Laboratory (ARL)[21].

1939, France, earliest proven attempted flight recorder "Type HB", a photograph-based flight recorder that cannot be erased or recycled. It was invented by Francoise Hussenot and Paul Beaudouin at the Marigname Flight Test Centre in France.[22]

c. 1939-1945, England, at Farnborough for the Ministry of Aircraft Production, another form of flight data recorder unit were developed by Len Harrison and Vic Husband. A unit that could withstand a crash and fire, which keeps the flight data intact by using copper foil as a recording medium.[23]

1941, France, 25 of "HB" recorder pre-production run were ordered. This HB recorder was used in the French Test Centre up until the seventies.[24]

1941, Australia, aircraft accident investigation began at ARL. [25]

1941, Australia, ARL Aerodynamics section under the leadership of Dr G N Patterson an experienced aerodynamicist (specialist in wind tunnel investigations in Britain)built Australia's first wind tunnel, the low speed wind tunnel began operation on 5 December 1941, 2 days before the bombing of Pearl Harbour.[26]

During the same period, Dr M W Wood, leading the Engines and Fuels section, concentrated on piston engines and fuels and lubricants. Complete change over to turbine aircraft engine at the end of war.

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[19](G., 1985)
[20](Aeronautical Research Labarotories, 1979)
[21](Aeronautical Research Labarotories, 1979)
[22](Wikipedia, 2014)
[23](Wikipedia, 2014)
[24](Wikipedia, 2014)
[25](Aeronautical research labarotories, 1979)
[26](Aeronautical research labarotories, 1979)

Mr HA Wills head the structures and materials section, investigation into air frame failure, structural strengthening to assist structural design. During war also researched alternative aircraft materials that depend on overseas supplies in this department.

1942, England, Brabazon Committee, a British government body proposed the development of a post-war airline aircraft, the aim was to build a civil type of aircraft that is ahead of its current technology, instead of competing with the American's leading "superb, highly efficient intercontinental military aircraft".

1942, Finland, Veijo Hietalaan Finnish aviation engineer created what is referred to as the "Meta Hari Recorder," one of the earliest modern flight recorders, a mechanical 'high tech' mechanical box, with the purpose of recording aviation flight details.[27]

1946, England, de Havilland Company begin to work on its pioneering design, a world first jet airliner known as DH-106 Comet after the proposal from Brabazon Committee on post-war aircraft for the British industry.[28]

1947, England, David Warren, a chemist, gains his knowledge on fuel combustion in England and was one of the few who got to see the first jet airliner prototype Comet. [29]

1948, Australia, ARL Aerodynamics Division started to operate a variable pressure wind tunnel with its research into subsonic, transonic and supersonic flight. [30]ARL was involved in the Commonwealth Advisory Aeronautical Research Council (CAARC).[31]

1949, Australia, Department of Supply and Development change its name to Aeronautical Research Laboratories (ARL) with 5 divisions. [32]

1949, England, prototype Comet 1made its first flight. [33] Comet offered the reduced travelling time from 3 days to 1 day between England and Australia.[34]

1951, Australia, ARL researching on supersonic aerodynamics initiated. [35]

1952, England, world first jet passenger service was scheduled with daily operation, BOAC Comet, initially between London and Johannesburg after receiving a full Certificate of Airworthiness. [36]

[27](Wikipedia, 2014)
[28](Job, 1996)
[29](Walby, 1993)
[30](Aeronautical research labarotories, 1979)
[31](Aeronautical research labarotories, 1979)
[32](Aeronautical research labarotories, 1979)
[33](Job, 1996)
[34](Walby, 1993)
[35](Aeronautical research labarotories, 1979)
[36](Job, 1996)

1952, September, England, de Havilland announce the development of Comet 3, with a longer range variant for Atlantic service. [37]

1952, October 26, Rome, first of a series of accidents that took place with British airline BOAC's Comet G-ALYZ at Rome's Ciampino Airport, during take-off at high speed on a rainy night. Occupants escaped injury however the plane was damage beyond repair.[38]

1953, March 3, Pakistan, during take-off of a Comet after refuelling on a fine day, an almost exactly similar but fatal accident took place as in Rome 4 months earlier, this time 5 flight crews and 6 passengers died during the crash. [39] "Without survivors, witnesses and apparent reasons", this lead to further investigation.[40]

2 month later a similar accident happened during Singapore and London operation.[41]

1953, May 2, India, another fatal accident occurred involving the Comet. From the sky a "blaze of fire" was seen because a Comet disintegrated in the air during a thunderstorm at night, it was believed to be a lightning strike, with flight crews of 6 and37 passengers all died. [42]

1953, Australia, ARL, a young scientist named David Warren was involved in the investigation of the world first commercial jet airliner de Havilland Comet after series of fatal incidents[43]

During the committee, discussing the possible cause, "Warren conceived of a crash-survivable method to record instruments readings and flight crew conversation" to help investigators ascertain the cause of the incident. [44]

The idea arose after Warren saw a German made miniature (pocket size) Minifon tape recorder that he wanted to purchase to record his own personal music.[45]He saw this device in an exhibition in Melbourne of technical equipment. [46]

1954, May, Australia, ARL, Warren publishes a report "A Device for Assisting Investigation into Aircraft Accidents". [47]

That same year, Australian Aeronautical Research Committee (AARC) was set up.[48]

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[37](Job, 1996)
[38](Job, 1996)
[39](Job, 1996)
[40](Gronow, 1999)
[41](Job, 1996)
[42](Job, 1996)
[43](Wikipedia, 2014)
[44](Wikipedia, 2014)
[45](Gronow, 1999)
[46](G., 1985)
[47]Appendix XX

1954, Australia, "ARL suggested that a small automatic recorder be developed for aircraft to assist investigation in the event of an accident". [49]

1954, April 12, England, Minister for Transportation and Civil Aviation withdraws the Certification of Airworthiness of all British registered Comet aircraft just four days after the lost of the Comet G-ALYY, and the loss of many more Comets earlier in India, Singapore, Africa, Naples and Elba. [50]

1956, Australia, ARL conducts major flight research on an Avro707A aircraft. [51]

1957, Australia, ARL, first basic Flight Data Recorder (FDR) demonstration unit was produced. [52] Warren built this prototype FDR called "The ARL Flight Memory Unit".[53]

1958, June (middle), Australia, ARL, "first coupled FDR with CVR prototype designed with civilian aircraft in mind" was produced. The aviation authorities around the world were not interested. [54]

Sir Robert Hardingham, the Secretary of British Air Registration Board was interested in the prototype when introduced to Warren during his visit to ARL.[55]Warren demonstrated the recorder to the group during lunch. [56]

1958, August, England, Warren flew to England to demonstrate his flight recorder to the British Ministry of Aviation which drew a keen interest toward the idea. [57]

1958, August 25, England, Warren gave a presentation to a mixed group of 60 interested parties at Transport House, Westminster, UK. The British were more impressed than the Americans, which lead to offering of publication and manufacturing in England. [58]

After the enthusiastic interest from the British, "ARL allocated Warren an engineering team to develop the prototype to airborne stage". This included "incorporating a fire and shock proof case, a reliable system for encoding and recording aircraft instrument readings and voice on one wire, and a ground-based decoding device". [59]

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[48](Aeronautical research labarotories, 1979)
[49](Aeronautical research labarotories, 1979)
[50](Job, 1996)
[51](Aeronautical research labarotories, 1979)
[52](National Geagraphic Channel, 2014)
[53](Wikipedia, 2014)
[54](Wikipedia, 2014)
[55](Wikipedia, 2014)
[56](Gronow, 1999)
[57](Gronow, 1999)
[58](Walby, 1993)
[59](Wikipedia, 2014)

Years later the ARL flight recorder system became “The Red Egg” made by British instrument making company S Davall& Son Ltd. [60]

1958, October, England, the public have the opportunity to fly again after BOAC introduce a “Re-designed and longer fuselage Comet 4 to the Atlantic service”, however 3 weeks later America’s Boeing took the market by storm by introducing a larger, longer 707 jetliner. [61]

1958, October, England, EMI manufacturing confirmed their interest in producing the recorder based on ARL’s design, and also indicated that they wanted the sole rights to produce the instrument. [62]

1959, May, England, EMI manufacturing withdraw their entire support for the Project (ARL’s flight recorders) as the company reported having difficulties obtaining supplies of Minifon recorders from German manufacturers Protona and a negative impact from their potential customer in the US .[63]

1960, June 10, Australia, Fokker F27 Friendship, Trans Australia Airline crashed at Mackay, Queensland, killing 29 people. This caused a judicial recommendation from the investigation Board of Inquiry that all commercial (turbine powered) aircraft be installed with flight recorders. [64]

1960, August, Australia, ARL, Mechanical Engineer superintendent made it clear that ARL intended to start testing flight recorders in January 1961. Warren outlined the testing program from March till September 1961. [65]

1960, September 5, Australia, many instrument manufacturing companies showed interest in constructing the flight recorder, including Davall, Penny, Gile and also EMI which had shown dis-interest in the project just months before.[66]

1960, November, Australia, Ministry of Aviation issues specifications which enable manufactures to produce suitable prototype recorders.[67]

1961, February 2, US, Cockpit Sound Recorder (CSR), invented and patented by Edmund A. Boniface Jr. an Aeronautical Engineer at Lockheed Aircraft Corporation under the file name “Aircraft Cockpit Sound Recorder”. Some pilots viewed the cockpit sound recorder as an

[60](Wikipedia, 2014)
[61](Job, 1996)
[62](Walby, 1993)
[63](Walby, 1993)
[64](National Geagraphic Channel, 2014)
[65](Walby, 1993)
[66](Walby, 1993)
[67](Walby, 1993)

invasion of privacy, Boniface then changed the design so that there was a spring loaded erase that the pilots could use to erase the recordings at the end of a successful flight.[68]

1961, March 9, Australia, Minister of Civil Aviation announced that all Australian Airlines would carry voice and data recorders. Australia was to become the first country in the world to make this mandatory. [69]

1961, April 24, Australia, meeting held at Melbourne, the DCA which had shown little interest in the ARL recorder years earlier, stated that due to lack of development the door may be close for the ARL recorders.

1961, September 7, Australia, two Australian airlines placed orders for 70 recorders from the American firm, United Data Corporation and 23 from Lockheed. The department of Civil Aviation found the recorder less than effective, because it was using scratch on foil techniques and plastic tape for speech recording[70]

1962, May 31, Australia, Government introduces regulations that required the Boeing 707 to carry flight recorders.[71]

1963, January 1, Australia, the Minister for Civil Aviation stated that it would soon be mandatory for all Australia airliners to be fitted with flight recorders. [72]

1963, England, British instrument making company S. Davall & Son, decided to go ahead with the production using Warren's model as a prototype [73] without ARL granting rights to the UK only company and without patent rights.

1963, October, Davall failed to get a contract to produce ARL flight recorders for British and European airlines and ceased the production. However the company continued to develop other recorders. [74]

1964, Australia, Mr L P Coombes retired from ARL (25 years leadership in ARL). [75]

1965, January 1, Australia, Government regulations require all aircraft over 12500 lb to be fitted with flight recorders, not just Boeing 707. [76]

1965, England, crash of jet passenger aircraft Vickers Vanguard installed with Davall's instrument based on Warren's design "Red Egg" have proven useful. [77]

[68](Wikipedia, 2014)
[69](G., 1985)
[70](G., 1985)
[71](Walby, 1993)
[72](Walby, 1993)
[73](G., 1985)
[74](Walby, 1993)
[75](Aeronautical research labarotories, 1979)
[76](Walby, 1993)

Later, the “Red Egg” redesigned and moved to the rear of the airplanes to improve the probability of successful data retrieval after a crash.[78]

1965, Australia, Qantas employee, Jack Grant invented the inflatable escape slide.

1967, Australia becomes the first country in the world to have both flight data and cockpit voice recorders mandatory. Since then the world followed and made it compulsory on all civil aircraft. [79]

1967, November, Australia, Department of Civil Aviation was forced to admit that flight recorders using magnetic wire (Warren’s design) is the way forward. This occurred 14 years after Warren’s invention.[80]

1981, Australia, Dr David Warren left ARL to become scientific adviser to the Victoria Parliament on energy resource.[81]

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[77](Walby, 1993)
[78](Wikipedia, 2014)
[79](K., 2001)
[80](G., 1985)
[81](G., 1985)

Appendix 5 Comet Story

Figure 4 G-ALYP the First De Havilland Comet(Wheater, 2012).

Appendix 6Comet Story

The De Havilland Comet was the first jet powered passenger aircraft in the world. Design of the Comet started in 1946 and went into production in 1949. The Comet had 4 Rolls Royce Ghost engines, could carry 36 passengers and cruise at 40,000 feet at 800 kph.[82]A series of misfortunes began for the comet in 1952 when one of BOAC's Comet's had to abandon takeoff at Rome in rain. In this incident no one was injured but the misfortunes of the Comet were about to become deadly. On March 3, 1953 a team delivering a Comet to Canada via Australia was taking off from Rangoon and over rotated on takeoff and collided with a culvert past the end of the runway killing all on board. In 1953 a Comet disintegrated 36 km from its takeoff at Dum Dum (Kolkata, India) Airport. The investigators concluded that the disintegration of the aircraft was due to overstressing of the tail plane due to severe

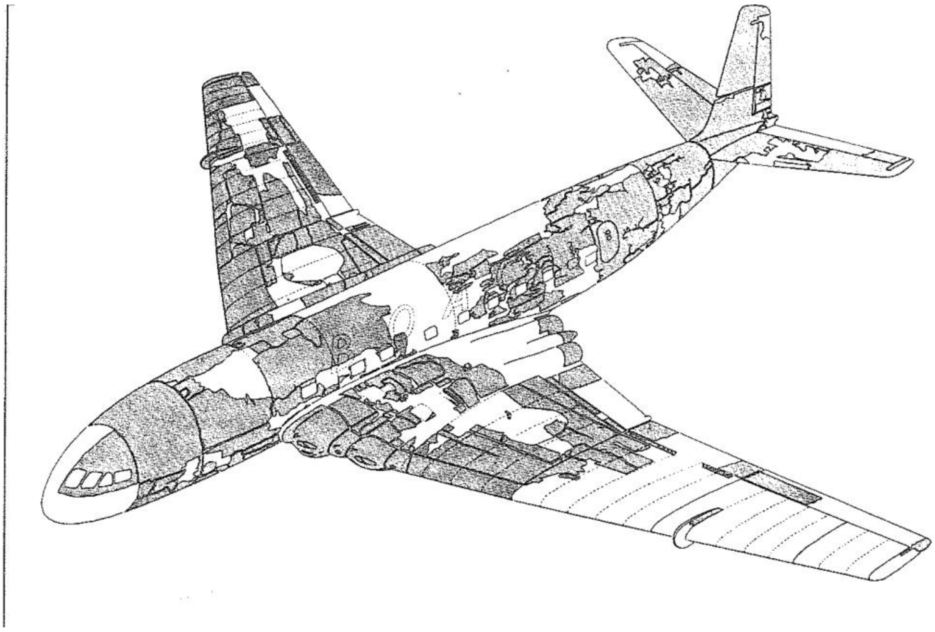

Figure 5 Diagram Showing amount of Wreckage of G-ALYP that was recovered near island of Elba(Job, 1996).

[82] Comet specifications (Job, 1996).

gusts in a thunderstorm. Eight months later another BOAC Comet was flying on its last leg from Rome to London when it exploded mid-flight. It was a nice crisp, calm morning with a very small amount of clouds, the Comet climbed through this quickly to its cruising altitude, at 0950 hours witnesses reported hearing a loud explosion and seeing the parts of the wreckage. Some of it on fire falling from the sky.

Figure 6 – Reconstruction of G-ALYP's fuselage and tail assembly at the Royal Aircraft Establishment at Farnborough during the investigation of G-ALYP and G-ALYY accidents(Job, 1996)

After this accident BOAC suspended all its scheduled Comet flights so that detailed examination and testing of the Comet could commence. Eleven weeks later, with no real reason emerging from the investigation as to what occurred, BOAC resumed Comet flights.[83] A fortnight later a Comet on loan to South African Airways disappeared near the volcanic island of Stromboli off the coast of Italy. The aircraft was found to have broken apart at around the same time and altitude as the previous accident.

BOAC immediately cancelled all Comet services again. Then on April 12 1954 the air registration board withdrew all Certificates of Airworthiness of all British registered Comet aircraft.[84]A desperate and intense search for the wreckage followed. The search lasted months and when the eventually found the pieces they discovered that a passenger seat had struck the tail before it came apart from the plane and blue paint from the aircrafts fuselage was found on the wings. This evidence signifies that the fuselage had a

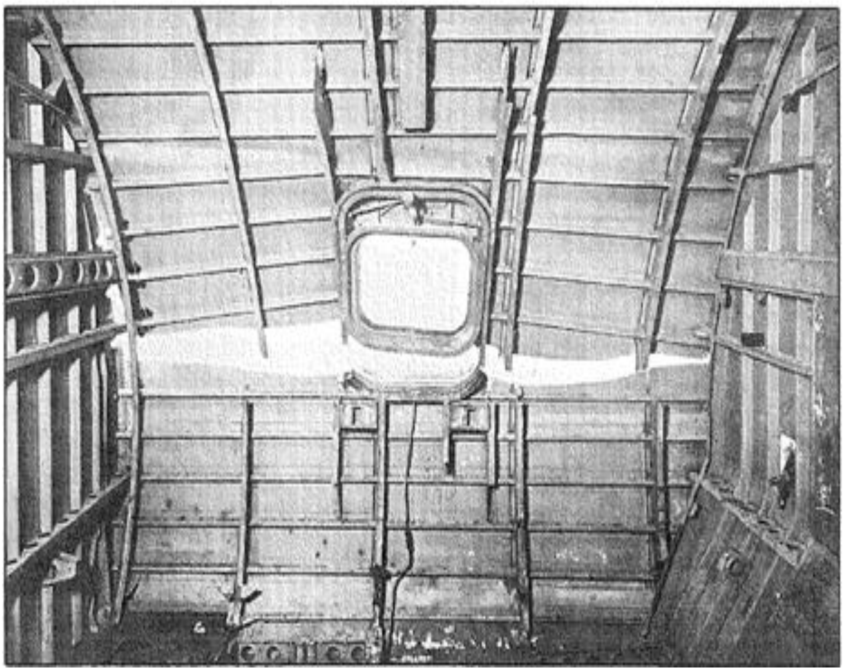

Figure 7- The port side window and escape hatch of a Commet which failed pressure tests in the test hatch (Job, 1996)

[83](Job, 1996)
[84](Job, 1996).

catastrophic failure before the aircraft came apart.

Part of the investigation into Comet failures entailed building a large hydraulic test tank in which a Comet fuselage was placed and subjected to repeated pressurisation cycles. This eventually (after a very large number of cycles) led to structural failure as show in Figure 7.

In the test tank the fuselage failed after 9000 hours, and the investigators found a split in the fuselage 3 m long and 30 cm high, the cause of this was found to be a hairline fracture at a rivet hole in the cut out for the forward escape hatch, a similar fracture was found at the rivets for the ADF antenna mount. Soon afterwards the fuselage of the wreckage was found to have the same fractures.

These discoveries caused the world to change aircraft design standards for pressurised jet aircraft. One of these were to fit smaller windows.
In 1958 the Comet 4 was released with all of the problems of Comet 1, 2, and 3 rectified. But three weeks later Boeing released its much bigger, longer range 707 jetliner. Britain's DeHavilland Company, the pioneer, had missed the bus.[85]

Figure - 8 Comet 4 (The Airways Museum & Civil Aviation Historical Society, n.d.)

Figure 9 - Boeing 707(airways news, 2015).

[85](Job, 1996).

Appendix 6 Australian Contribution to Air Safety

The Black Box: An Australian Contribution to Air Safety

A brief description of the ARL[1] invention written on 16 July 1998 by

Dr David Warren[2]

and

Ken Fraser[3]

[1] ARL refers to the Aeronautical Research Laboratories which at the time of the invention was part of the Australian Commonwealth Government Department of Supply. ARL later became DSTO (Defence Science and Technology Organisation) Melbourne, part of the Australian Commonwealth Government Department of Defence.

[2] Inventor of the Black Box and formerly a Principal Research Scientist at the DSTO Melbourne Laboratory.

[3] Contributor to the development of the pre-production prototype Black Box (validated in flight tests in 1962) and a Principal Research Scientist at the DSTO Melbourne Laboratory at the time this document was written.

The Black Box:
An Australian Contribution to Air Safety

With jet aircraft now a common sight, it is hard to think back to the days of the world's first commercial jet aircraft. Following the rapid development of jet fighters during the Second World War, the British began to develop the first jet-powered airliner, the famous Comet, which first flew in the 1950s. But the Comet seemed to be cursed, and in 1953 a number of the aircraft crashed inexplicably, putting doubt in the public's mind about the safety of jets.

Aircraft engineers and scientists all round the world were also perplexed. The cause of the crashes had to be found or the Comet would be doomed to failure. Many professional committees discussed the possible causes at endless meetings. Dr David Warren of the Aeronautical Research Laboratories in Melbourne, a chemist specialising in aircraft fuels, was one of those involved with some of these meetings, his role being to consider whether a fuel explosion could account for the crashes.

Unfortunately, there were few clues to be found. There were no witnesses, no survivors, and all that was left of the aircraft were massive tangles of bent metal.

As David Warren listened to the frustrating discussion of possible causes, he began to conceive the idea of some sort of recording of the flight crew's conversation, and of protecting the record so that it would survive the crash. He reasoned that while the technical committees found it difficult to trace the cause of the crash, there was a good chance that that the flight crew might have known, and it might well have been revealed in their conversation in trying to deal with the emergency.

Warren discussed his concept openly, but found it raised very little interest. So, in 1954, he outlined his ideas in a report entitled "A Device for Assisting Investigation into Aircraft Accidents". This was circulated widely to aviation authorities and the aircraft industry, but also appeared to evoke little interest.

It was decided that "show and tell" would be more effective than "tell", so a demonstration unit was needed. With the enthusiastic support of his Superintendent, Mr Tom Keeble, and an Instrument Engineer, Mr T. Mirfield, such a unit was designed and built using steel wire as the recording medium. It was fully automatic for fit-and-forget operation with a "memory" mechanism that would store four hours of pilot voice and instrument readings at the rate of eight per second up to the moment of any accident, but would automatically erase older records for the wire to be re-used. It was given the project name of "The ARL Flight Memory Unit" and the original (Figure 1) is now displayed in the Science Museum, Melbourne.

Figure 1: The original (1958) ARL Flight Memory Recorder, capable of storing the cockpit speech and eight instrument readings per second for the four hours prior to an accident.

After being successfully tested in the air, assessment by the various aviation authorities was formally requested. The response was far from encouraging. Civil authorities replied that "Dr Warren's instrument has little immediate direct use in civil aircraft". The RAAF considered

"such a device is not required - - - the recorder would yield more expletives than explanations". The Australian Aeronautical Research Council recommended "in view of the difficulties involved no action should be taken". The Federation of Air Pilots declared that it would be like "a spy flying alongside - - - no plane would take off in Australia with Big Brother listening".

The reason for this widespread local disinterest may well have been that Australia had not experienced a major air accident for many years and, indeed, was recognised as having the world's best safety standard at that time. "We don't have accidents any more" seemed to be a general feeling, so "selling crash recorders in Australia was like selling ice cream to Eskimos".

This stalemate was finally broken in 1958 when the Secretary of the UK Air Registration Board, Sir Robert Hardingham, happened to see the recorder while on an informal visit to ARL. His enthusiasm was instantaneous. He arranged for Warren to take the "Flight Memory" to England to demonstrate it. The response to the demonstration in the UK was most encouraging. The BBC featured the recorder on evening television and Radio Newsreel. Many UK manufacturers and operators offered their support, and the British authorities began a move to make recorders mandatory in British civil aircraft.

Warren was given a team, comprising Lane Sear, Ken Fraser and Walter Boswell, to update the early model Flight Memory to a pre-production standard. It was improved (Figure 2) in a number of ways, including a method of recording instrument readings with greater accuracy and at an increased rate of 24 readings per second. In anticipation of the coming mandatory requirement, the British firm of S. Davall & Son approached ARL for the production rights and their "Red Egg" crash recorder was developed from it, winning a large part of the British and overseas market at that time.

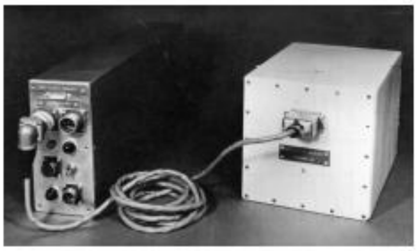

Figure 2: The "pre-production" prototype ARL Flight Memory Recorder (1962) with the recording mechanism in a separate crash-and-fire-proof container for mounting in the tail of the aircraft.

Figure 3: The playback station used for separating the cockpit speech and analysing the instrument readings.

Progress in Australia had to wait till the unexplained crash of a Fokker Friendship in Mackay, Queensland, in 1960. The judge inquiring into the mysterious crash was told of the development of the crash recorder and, as a result, made a judicial order that all Australian airliners should carry recorders for pilot speech as from January 1963. Unfortunately, although the Flight Memory system was offered as an immediately-available answer, a decision was made to ask an American company, United Data Control (UDC), to develop a cockpit voice recorder to meet the Australian requirement. UDC chose to use magnetic tape which was harder to make fireproof than wire, and led to delays in its development. When Australia's next aircraft accident occurred in Winton, Queensland, voice recorders had still not been fitted, and questions were asked at the inquiry about the failure to comply with the judicial

requirement. However, soon afterwards, in 1967, the difficulties were overcome and, while the UK and other countries had adopted the recording of flight instrument data, Australia became the first country to make both flight data and cockpit voice recording mandatory.

Voice-plus-data recording is now mandatory for all major civil aircraft throughout the world and has proved to be of inestimable value in finding the causes of many aircraft accidents, just as its inventor, Dave Warren, had foreseen.

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Addendum for the Technically Minded

The ARL pre-production prototype ARL Flight Memory Unit (1962) comprised *an ARL Flight Memory Recorder*, an associated *ARL Flight Memory Electronics Unit* which did not have to survive a crash, and a ground station unit named the *"ARL Flight Memory Ground Equipment"* which was used to unscramble the recorded data. The Recorder was essentially a small, light-weight recorder capable of storing the cockpit conversation and flight data for an aircraft during a period of four hours before an accident. Speech and eight channels of flight data were recorded together on magnetic wire using a combination of frequency and time multiplexing. The wire was made of special steel and was 0.005 mm in diameter. The flight data signals were taken from transducers and time-multiplexed at a rate of 24 readings per second by means of a solid-state sampling switch that switched bursts of a recordable carrier frequency. The different frequency bands for speech and flight data allowed them to be separated by the ground station equipment (Figure 4).

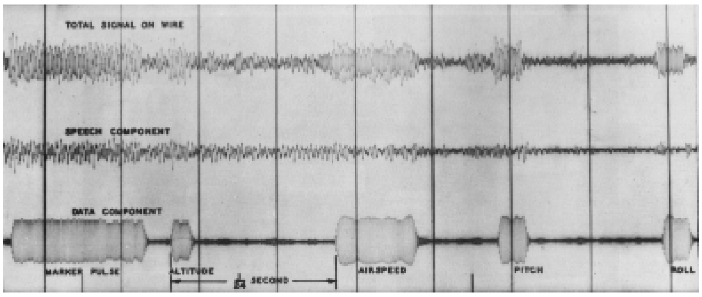

Figure 4: Cockpit speech and instrument-readings separated by the playback station.

The choice of the recording method presented a scientific challenge. Basically, magnetic wire is a single channel medium (compare with the multi-track possibilities for magnetic tape) and, unlike the tape recorder, the wire recorder does not have a capstan to feed tape past the recording head at constant speed as the spools turn. There was no guarantee that the layering of the wire when recording and when reproducing would be the same and fluctuations in signal frequency between recording and reproducing were apparent. The method adopted was to convert the pulse duration for each flight data channel into the number of cycles of a sinusoidal carrier. The number of cycles remained invariant even if the carrier frequency fluctuated between recording and reproducing. This was a pseudo-digital recording method for the flight data and provided remarkably good accuracy. The pre-production prototype was installed in the Department of Civil Aviation Fokker Friendship aircraft, VH-CAV, and the maiden test flight took place on 23 March 1962 departing from Essendon airport (in Melbourne, Australia). A sample of the instrument readings recorded during that flight and decoded by the playback station is shown in Figure 5.

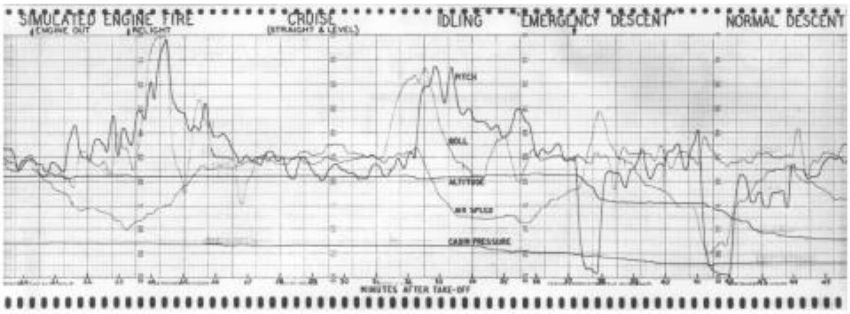

Figure 5: Chart printout of instrument readings recorded during the test flight of the pre-production prototype and decoded by the playback station.

Wire was chosen as the recording medium because it could withstand a higher temperature than tape during any post-crash fire and, at the time of the development of the system, it was superior to tape in terms of storage capacity per unit volume of magnetic medium. Even so, the wire spools were protected against fire and impact damage via a protective box. In subsequent years there was a world trend to switch from magnetic wire to tape as the preferred recording medium. Magnetic tape has, in recent times, been superseded by computer-style technology using solid-state memory chips.

Appendix 7 Black Box Flight Data and Voice Recorder Team

1.0 Dr David Warren

Dr David Warren AO, BSc (Sydney), PhD (London), DIC, DipEd (Melbourne), FAIE.

1.1 Background

David Warren (1925-2010) was born in 1925 at a remote mission station on Groote Eylandt in the Gulf of Carpentaria, North Australia. He was the first European child to be born on Groote Eylandt. To ensure a good education, he was "sent south" at age four, to spend most of the next 12 years in boarding schools (mainly Launceston Grammar and Trinity Grammar, Sydney).[86]

In 1934, David's father was killed in one of Australia's earliest air disasters, the loss of the Miss Hobart in Bass Strait. His last gift to David was a crystal set. David found he could listen to the set after lights-out in the school dormitory and became interested in electronics. He began building radios as a schoolboy hobby and enrolled for the public examination to become, he hoped, Australia's youngest "radio ham". When the sudden war-time ban on amateur radio dampened David's hopes, he turned to chemistry as a hobby and, ultimately, a life-time profession. However, his schoolboy knowledge of electronics stood him in good stead when, many years later, when he decided to design and build the world's first flight data recorder, now widely known as the "black box".[87]

David was involved in the accident investigations related to the mysterious crash of the world’s first jet-powered aircraft, the Comet, in 1953. He argued that a cockpit voice recorder would be a useful means of solving otherwise unexplainable aircraft accidents. The idea initially raised little interest, so David decided to design and build an experimental unit to demonstrate the concept. It could continually store up to four hours of speech, prior to any accident, as well as flight instrument readings. It took five years before the value and practicality of the idea was finally accepted. It was another five years before it became mandatory to fit cockpit recorders in Australian aircraft. The modern-day equivalent of David’s device is now installed in passenger airliners around the world.[88]

Professionally, David's interests have been divided between technical education and scientific research:[89]

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[86](DSTO, 2015)
[87](DSTO, 2015)
[88](DSTO, 2015)
[89](DSTO, 2015)

- 1944-46 - Teacher of mathematics and chemistry, Geelong Grammar School, Victoria.
- 1947-48 - Lecturer in chemistry, University of Sydney.
- 1948-51 - Scientific Officer, Woomera Rocket Range and Imperial College, London.
- 1952-83 - Principal Research Scientist, Aeronautical Research Laboratories, Melbourne, now part of the Defence Science and Technology Organisation.
- 1981-82 - Scientific Adviser (Energy) to the Victorian State Parliament.

David has also served in many voluntary positions, including as chairman of the Combustion Institute (Aust & NZ Section) for 25 years (1958-83), and as a committee member of the Chemical Society, the Institute of Fuel, and the Australian Institute of Energy.[90]

David's other interests have included lecturing and organising meetings for the Council of Adult Education, Probus Groups, the Forum Society, the Rationalist Society, and the Morris Minor Car Club of Victoria, of which he has been founding chairman and patron for 25 years (1977-2002).[91]

While a student at the University of Sydney, David met Ruth Meadows, who became his wife and lifetime supporter. Together, they have raised a family and shared an interest in science and education, arranging many educational tours in conjunction with international conferences.[92]

In recent years, David has received a number of awards in recognition of his contributions to aeronautics and energy research, including:

- The Australian Institute of Energy Medal, 1999.
- Hartnett Medal of the Royal Society of the Arts, 2000.
- Lawrence Hargrave Award of the Aeronautical Society, 2001.

In 2002, he was officially recognised in the 2002 Australia Day Honours list, being appointed an Officer in the General Division of the Order of Australia for his "service to the aviation industry, particularly through the early conceptual work and prototype development of the black box flight data recorder".[93]

[90](DSTO, 2015)
[91](DSTO, 2015)
[92](DSTO, 2015)
[93](DSTO, 2015)

Figure 1 – David Warrens Lawrence Hargrave Award

1.2 Flight Recorder Project

The idea to create a cockpit voice recorder was David Warren's idea, and because of this he was the team leader for this project and he ultimately received the credit for the creation of this device.

While David Warren was investigating the mysterious crash of the world's first jet-powered airliner he thought back to a trade fair that he had recently attended where he saw the world's first miniature recorder. It was this miniature recorder that gave David Warren the idea for the cockpit voice recorder.

Dr Warren, who was a combustion/fuels specialist, was one of those involved with some of the meetings about the mysterious crashes of the comet aircraft, his role being to consider whether a fuel explosion could account for the crashes. [94]

Dr Warren, at age 29, first published his accident recorder concept in 1954. Basically his proposal included:

- Cockpit voice recording (CVR).
- Magnetic wire recorder of small time-span with continuous over-write capability.

Dr Warren referred to his invention as the "ARL Flight Memory system". The term "black box" was believed to have been attributed to a journalist. In the early days black box was in common usage for such things as a mystery box of electronics for which the main interest was in what it does rather than how it works. Black Box has now become the accepted term for accident recorders even though, for aircraft, a readily distinguishable orange colour is standard.[95]

2.0 Kenneth Fraser

2.1 Background

Ken Fraser graduated with honours from the University of Melbourne, Victoria, Australia, with a Bachelor of Electrical Engineering Degree in 1959. He spent his working career in the field of aeronautics as an employee of the Australian Defence Science and Technology Organisation, a major research arm of the Department of Defence. He retired in 2002 as Principal Research Scientist in charge of the Helicopter Life Assessment area.

[94](Fraser, 2008)
[95](Fraser, 2008)

During his career, he worked in various aeronautical fields mainly in relation to military aircraft operated by the Australian Defence Force. Research areas included crash data recording, air vehicle kinematics, propulsion data systems, turbine engine health monitoring, turbine engine control, helicopter gearbox life assessment, aircraft Health and Usage Monitoring Systems (HUMS), and helicopter structural integrity. A major part of the scientific work on helicopter structural integrity, performed in the last 10 years before he retired, was in support of the Black Hawk helicopter operated by the Australian Army.[96]

Some achievements

He was involved in the development and flight demonstration of the world first "black-box" aircraft crash data recorder that recorded both cockpit voice and flight data on a magnetic wire medium.[97]

He was the first person at the Aeronautical Research Laboratory (as it was then known) to apply position matrices to analyse the kinematics of air vehicle motion. That work was done a long time before digital computers became available and eventually became the standard approach.[98]

He developed a system for in-flight monitoring of the accumulated fatigue damage to heavily loaded helicopter gears. It was the first time a full fatigue damage calculation, that included component strength characteristics, had been performed during flight in a helicopter. The data system used for the in-flight fatigue damage calculation was called a Fatigue Life Usage Indicator (FLUI). The data system invention (with co-inventor U.R. Krieser) was granted an Australian Patent No. 550667 on 2 September 1981, a Canadian Patent No. 1181851 on 29 January 1985, and a US Patent No. 4733361 on 22 March 1988.[99]

He introduced a novel way of analysing thermocouple temperature measuring circuits whereby each junction is represented by an open circuit voltage generator in series with a junction/lead resistance. The normal approach is to start with a closed circuit which is fine when dealing with simple circuits. Conventional network analysis and superposition techniques were used to analyse an aircraft engine turbine inlet circuit that involved 18 tightly coupled hot junctions and a cold junction.[100]

He pioneered the setting up of an Australian Defence Organisation Working Party (with Air Force, Navy and Army representation) that provided guidance on the applicability of accident data recorders and HUMS to Australian Defence Force aircraft. DSTO's scientific work on HUMS, from a system's perspective, was subsequently led by Graham Forsyth

[96](Fraser, 2008)
[97](Fraser, 2008)
[98](Fraser, 2008)
[99](Fraser, 2008)
[100](Fraser, 2008)

(retired) who is well known internationally, particularly as organiser of regular (every two years) HUMS conferences.[101]

From 1992 to his retirement he was head of a Helicopter Life Assessment functional area of about 10 staff who were mainly involved in helicopter structural integrity research and experimental investigations. The majority of this work was focussed on the support of the Black Hawk helicopter operated by the Australian Army. Major work included a Black Hawk flight test program to investigate the cause of cracking of an inner fuselage panel and participation in a major structural integrity flight survey conducted by the Australian Defence Force in collaboration with the United States Air Force, with Georgia Tech Research Institute and Sikorsky as main contractors. The survey was purported to be the most extensive survey of its kind ever performed on a helicopter. During the time he was head of Helicopter Life Assessment, he was ably assisted by D.C. Lombardo (Domenico) who is currently DSTO's lead specialist in the area.[102]

2.2 Flight Recorder Project

Kenneth Frasers' involvement in the flight recorder project started in 1961 with the aim to update the early model of the flight data recording system to a preproduction standard suitable for recording cockpit voice and data[103] in a fireproof and crash proof casing.

Kenneth Fraser also had a 1/3rd involvement in the design of the airborne systems (signal circuit design) as well as designing the high power system (recorder drive etc). Kenneth Fraser also had 2/3rds involvement in the data recovery and audio circuits used in the airborne unit

3.0 Walter Francis Lane Sear (Lane Sear)

Lane Sear was a qualified electrical designer who had equal share of the final design as Ken Fraser.

Lane Sear had 2/3rds of the airborne system (signal circuit design), he also had a 1/3rd involvement with the data recovery and audio circuits used in the airborne unit.

4.0 Walter Boswell

Walter Boswell was a technical assistant who converted the designs of Ken Fraser and Lane Sear into usable hardware.

[101](Fraser, 2008)
[102](Fraser, 2008)
[103](Fraser, 2008)

Appendix 8 Paper by David Warren 'A device for assisting investigation into aircraft accidents,' April 1954

COMMONWEALTH OF AUSTRALIA

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AERONAUTICAL RESEARCH LABORATORIES

Mechanical Engineering Technical Memorandum 142

A DEVICE FOR ASSISTING INVESTIGATION INTO AIRCRAFT ACCIDENTS

by D.R. Warren

MELBOURNE April 1954

LE.

DEPARTMENT OF SUPPLY

RESEARCH & DEVELOPMENT BRANCH

AERONAUTICAL RESEARCH LABORATORIES

Mechanical Engineering Technical Memorandum 142

A DEVICE FOR ASSISTING INVESTIGATION INTO

AIRCRAFT ACCIDENTS

by D.R. Warren

PROBLEM STATED

The occurrence of a number of major air disasters in recent months has emphasised the need for determining with the greatest possible certainty the cause of such accidents. This is particularly true in the case of aircraft in the early stages of development, or those incorporating radical advances in design, construction or performance. One can never overlook the possibility that these accidents may be due to some unforseen weaknesses inherent in the design, and liable to lead to further disasters before they are pinpointed and remedied.

This is well illustrated by the recent "Comet" disasters. It will probably never be known with certainty whether these were due to structural failure, meteorological abnormalities, error-of-judgment, overcontrol by the pilot or to some sudden event of which the crew could have no warning or knowledge, such as a fuel-tank or sabotage explosion. Nor is it known whether these disasters had any basic factors in common

In investigating such accidents, therefore, anything which provides a record of flight conditions, pilot reactions, etc. for the few moments preceeding the crash is of inestimable value.

PRINCIPLE OF THE SUGGESTED DEVICE

It may be assumed that in almost all accidents the pilot receives some pre-indication either by sight, feel of controls, automatic alarm or instrument reading. In most cases this would evoke a complaint of difficulty or a shout of warning to attract the attention of the co-pilot. Unless radio contact is actually in progress there is often not time to get any information through before the crash.

To preserve the valuable evidence offered by these few seconds conversation it is suggested that the following simple device could be fitted in all major aircraft, especially those in early stages of development. A small magnetic recorder could be made in which a continuous closed circle of steel wire passes an erasing head followed by a recording head in, say, a 2-minute cycle. Such a device would, therefore, provide a permanent "memory" of the conversation in the control cabin for the two minutes immediately prior to switching off, which would occur automatically in the case of an accident.

This period is probably all that is required to give a clue to the trouble encountered. In the case of fire the period would almost certainly contain a shout from the first crew-member to detect it, followed by verbal instructions. Careless control or error-of-judgment (as is often suspected in landing and take-off accidents) would probably elicit criticism, suggestion or warning from the co-pilot. An unexpected fuel-tank explosion would be recorded as an interruption of normal conversation by the

first part of the explosion noise followed by immediate cut-out.

SIZE, WEIGHT AND COST OF THE DEVICE

The instrument would be much less in size, weight and cost than a normal wire recorder since neither high fidelity nor play-back facilities are required, and the amount of wire needed is very small (e g 30 ft.). Power supply requirements would be low and could possibly be taken to some extent from the existing radio system. Members of A.R.L. Instruments Section have offered a rough estimate that the total weight (using existing power supplies) need not exceed 5 lb., the space less than 0.1 cu ft. and the cost of production (dozen lots) £60.

RECOVERY OF THE WIRE

The wire itself would not be greatly harmed by impact nor by suffering moderate heating, though the extent of the latter would need to be checked by experiment. There are, therefore, two methods of ensuring its recovery after an accident.

(i) The unit could be installed in the least likely part of the plane to receive extensive damage. The tail is suggested, as it is often thrown clear. Even in the event of fire it is usually the part least subject to intense heat.

(ii) The device could be so installed that in the event of an accident it would be thrown clear of the main body of the plane. This could be done by a small charge or mechanical ejector triggered by any of a number of possible events, e.g

(a) Air speed rising above a maximum value

(b) A jolt of more than, say, 10g.

(c) A break in any part of the control circuit.

(d) The attainment of a given temperature.

The first would cover most accidents in flight. Those on landing and take-off would be covered by the latter ones.

If the containing box were reasonably robust no parachute would be required, as only the wire need be salvaged. An attached marker streamer, however, would greatly help in finding the unit.

MAINTENANCE REQUIRED

Once installed the unit could virtually be forgotten. It could be automatically switched on with the engines and thus would not place any further burden on crew responsibility. An occasional check that it was in working order could easily be included in routine ground service procedure with the aid of a portable play-back device.

PSYCHOLOGICAL EFFECT

The possible objection by crew to having their conversation continually recorded is countered by the fact that the device has such a short memory. If no accident occurs, anything said during flight is obliterated during the time taken to taxi in.

POSTAL ADDRESS: The Chief Superintendent, Aeronautical Research Laboratories, Box 4331, G.P.O., Melbourne.

Appendix 9 Drawing of interpretation Panel

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Change Control Log

Version 1- 15/2/2015	**Word Count: 3258**
Version 2- 26/2/2015	**Word Count: 6488**
Version 3- 10/03/2015	**Word Count: 6533**
Version 4-17/03/2015	**Word Count: 9489**
Version 5-31/03/2015	**Word Count: 10,519**
Version 6-04/04/2015	**Word Count: 11,082**
Version 7- 30/04/2015	**Word Count: 11,221**
Version 8- 1/07/2015	**Word Count: 11,423**